Integration of Space Geodesy: A US National Geodetic Observatory

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Abstract

In the interest of improving the performance and efficiency of space geodesy a diverse group in the U.S., in collaboration with IGGOS, has begun to establish a unified National Geodetic Observatory (NGO). To launch this effort an international team will conduct a multi-year program of research into the technical issues of integrating SLR, VLBI, and GPS geodesy to produce a unified set of global geodetic products. The goal is to improve measurement accuracy by up to an order of magnitude while lowering the cost to current sponsors. A secondary goal is to expand and diversify international sponsorship of space geodesy. Principal benefits will be to open new vistas of research in geodynamics and surface change while freeing scarce NASA funds for scientific studies. NGO will proceed in partnership with, and under the auspices of, the International Association of Geodesy (IAG) as an element of the IGGOS (Integrated Global Geodetic Observation System) project. The collaboration will be conducted within, and will make full use of, the IAG's existing international services: the IGS, IVS, ILRS, and IERS. Seed funding for organizational activities and technical analysis will come from NASA's Solid Earth and Natural Hazards Program. Additional funds to develop an integrated geodetic data system known as INDIGO (Inter-service Data Integration for Geodetic Operations), will come from a separate NASA program in Earth science information technology. INDIGO will offer ready access to the full variety of NASA's space geodetic data and will extend the GPS Seamless Archive (GSAC) philosophy to all space geodetic data types.

Introduction

The story of space geodesy is one of dramatic advance that has seen global measurement accuracy improve from multiple meters with satellite Doppler positioning in the 1960s to just a few millimeters with an assortment of techniques today. In the late 1970s, when global accuracies hovered near a meter, a speaker at the fall AGU meeting was asked, "When will we see a direct measurement of tectonic plate motion?" At the time, the idea that continents drifted over the earth's surface, though an old one, had been widely accepted for only about a decade, and no direct observation of the (presumed) steady motion of plate interiors had been made. "Sometime within the next one to 100 years" was the speaker's cautious reply. That was also about the time NASA, in response to this revolution in geophysics, formed its Crustal Dynamics Project (CDP)[1] with the express goal of devising the needed technologies and charting the motion of the tectonic plates. The speaker's reply neatly captured the sense of the community, which, mindful of the challenges in finding the required two orders of magnitude improvement, could not be confident of early success. As it happened success came fairly soon, with both very-long-baseline interferometry (VLBI) and satellite laser ranging (SLR) offering definitive confirmation of ongoing plate motion by the mid 1980s, joined by the Global Positioning System (GPS) a few years later.

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This rapid progress was abetted by the hospitable climate within the CDP, which brought together researchers from the three technology disciplines in workshops twice each year, fostering a vigorous commerce of ideas and a constructive, if often intense, competition among research groups. From there the history of our science might have proceeded rather differently than it did. The structures established by the CDP, which was joined by many international partners, might have been consolidated into an International Space Geodetic Service with continued joint workshops leading to tight coordination and thoughtful integration of the techniques. Instead, having accomplished their chartered objectives, NASA in effect declared victory and dissolved the CDP in 1991. In its place they instituted the Dynamics of the Solid Earth (DOSE) program, which emphasized geophysical research. Joint technology workshops disappeared and the three techniques in the U.S. – VLBI, SLR, and GPS – were left to pursue their interests separately, refereed by the funding agencies, rather than as cooperating elements of a unified space geodetic enterprise. We then saw the independent establishment of the individual technique-based services: the IGS in 1992[2,3], the ILRS in 1998[4,5], and the IVS in 1999[6,7]. As a result, the sense of community across techniques eroded, rivalries solidified, and efficient grass-roots coordination gave way to increasingly fractious and self-interested scrapping for scarce sponsor funds. This has led to inefficiency and is one reason for the now precarious status of SLR within NASA. In the end, Earth science is the loser.

Things are now beginning to turn around. In its report, *Living on a Restless Planet*[8], NASA's Solid Earth Science Working Group (SESWG) highlighted the critical functions served by the geodetic networks:

> *Precise 3-D crustal motions are determined by all three networks, with dense GPS arrays particularly useful for regional tectonic and earthquake cycle studies. Beyond their scientific value, these data, together with precise determination of the 3-D geocenter motion by SLR and GPS, constitute the geodetic elements that define the International Terrestrial Reference Frame (ITRF), which is the basis for all geodetic measurements described in this report. The ITRF is geometrically connected to the Celestial Reference Frame via Earth Orientation Parameter (EOP) time series, which are determined primarily by the VLBI technique and contain a wealth of geophysical and climatic information. The ITRF and EOP, and hence the networks, should continue to be maintained and improved and their data routinely acquired at the best possible accuracy and temporal resolution.*

NGO and IGGOS[9-16] offer a thoughtful response to this mandate. IGGOS is a broadly based movement to integrate the activities of an increasingly diverse international roster of space geodetic techniques. But IGGOS cannot by itself address the peculiar internal challenges facing NASA in sustaining a mature program in space geodesy while directing adequate resources to the scientific research that program is meant to support. Consolidation, coordination, and cooperation at the deepest levels among NASA-supported groups are vitally needed.

It was with that purpose that a diverse team representing the major space geodetic techniques submitted a proposal to NASA in 2002 to establish a National Geodetic Observatory. The NGO would bring together all major players in the U.S. under a self-governing federation, integrating them into a constructive alliance and providing a forum for emerging techniques to connect with the broader community and establish their legitimate roles. Figure 1 depicts the variety of space geodetic techniques now in operation. In addition to the big three we show lunar laser ranging (LLR), the last operating science experiment from the Apollo moon landings; DORIS, a now well-proven technique taking its place beside the others; altimetry, which can take myriad forms; the CHAMP and GRACE gravity missions; and the emerging technique of interferometric synthetic aperture radar, or InSAR. While the initial focus of NGO is on the three primary techniques – VLBI, SLR, and GPS – it is hoped that over time its scope will encompass the common interests of the newer entrants as well. Indeed, this is essential if NGO and IGGOS are to adapt to the advances of our science.

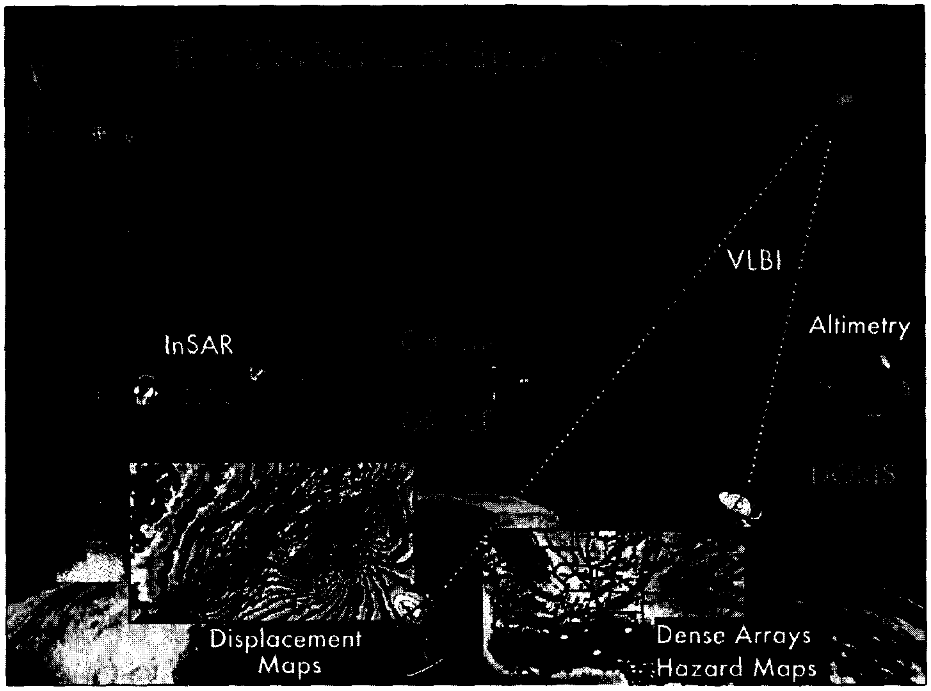


Fig. 1. Diverse forms of space geodesy now in operation.

The NGO proposal was intended largely to support the considerable organizational effort required to bring the federation into being. In the fall of 2002 we followed this with a second, more substantial proposal, known as INDIGO (INter-service Data Integration for Geodetic Operations), to put some implementation muscle into the project – specifically, to build an integrated data and information system for the three NASA-supported space geodetic operations. In 2003 both proposals received NASA support, though initially at considerably reduced levels. In close coordination with the broader IGGOS effort we are now beginning the hard work of bringing this vision to fruition.

NGO Objectives

NGO seeks to have space geodesists in the US work cooperatively, in concert with their international counterparts, to forge a unified system architecture and develop joint goals, priorities, and proposals guided by a shared strategic vision. A principal aim is to bring stability and continuity to providers and users alike while improving measurement accuracy and operational efficiency, nurturing emerging techniques, adapting to changing needs, and reducing the cost to current sponsors. This effort faces many challenges, technical, programmatic, and political. Only by bringing together the leaders of space geodesy programs worldwide can we hope to meet them effectively. At this early stage we envisage the following program of tasks:

- Review the current state of space geodesy:
  - Catalogue the geodetic products, services, and associated costs of each technique
  - Document current system performance and the expected evolution of requirements
  - Analyze interdependencies and identify possible synergies between current services
  - Identify performance limitations and prospective technology enhancements

- Develop the analytical underpinnings of integrated space geodesy:
  - Study how best to integrate disparate measurement types for maximum performance
  - Conduct trade studies and experiments to address such questions as the proper data mix for different tasks, where to deploy observing sites, and how to ensure integrity

- Unify the planning and operations for space geodesy within NASA and internationally:
  - Establish a cross-technique oversight body, or federation, in the US to plan and oversee the day-to-day activities of the NGO.
  - Develop a Strategic Plan to guide planning, proposals, and policies
  - Sustain the SESWG process and enact the SESWG vision for global geodesy.
  - Prepare for integration of developing space geodetic techniques, including altimetry, InSAR, space gravity, and magnetometry

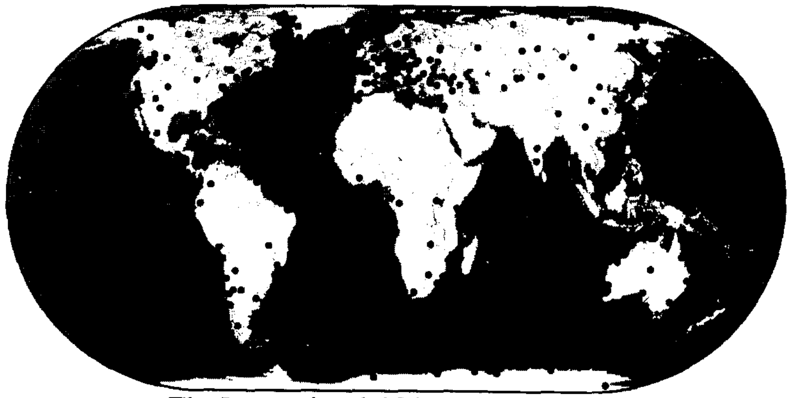
- Broaden sponsorship by enlisting the many institutions and agencies that use and benefit from space geodetic products.

This, to be sure, is more than a single small grant can achieve by itself. The intent is to seed the NGO development by providing planning and technical support; to provide, in effect, a lever with which to steer the more substantial resources and energies of our home centers and sponsors to advance the cause of space geodesy integration.

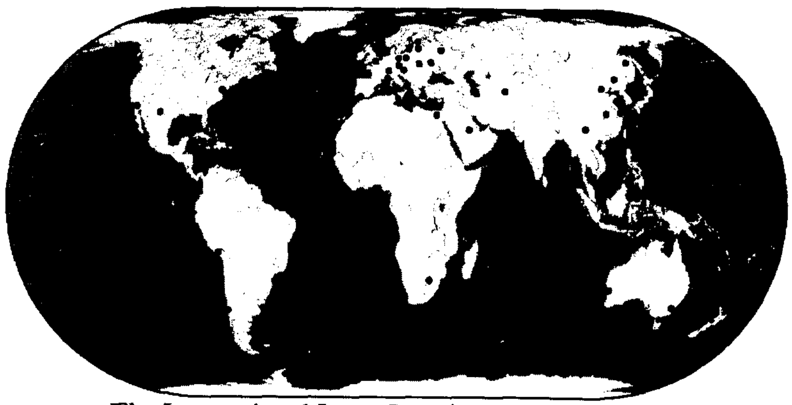
The IAG/IGGOS Umbrella

Success will require the good faith commitment of all major partners in space geodesy, not just within the U.S. but worldwide. The proper umbrella under which to carry this out is the International Association of Geodesy (IAG), parent organization of the international services for SLR (the ILRS), VLBI (the IVS), and GPS (the IGS), and for the cross-technique International Earth Rotation Service (IERS)[17,18]. NGO will be conducted as an integral element of IGGOS under the official auspices of the IAG, working through the four international services. With NGO we hope to create an enduring unification of space geodesy within NASA and the US, and at the same time help bring the international effort to fruition. To achieve this U.S. NGO team is joined by an international cadre of co-investigators, including the full Preliminary Planning Committee for IGGOS.

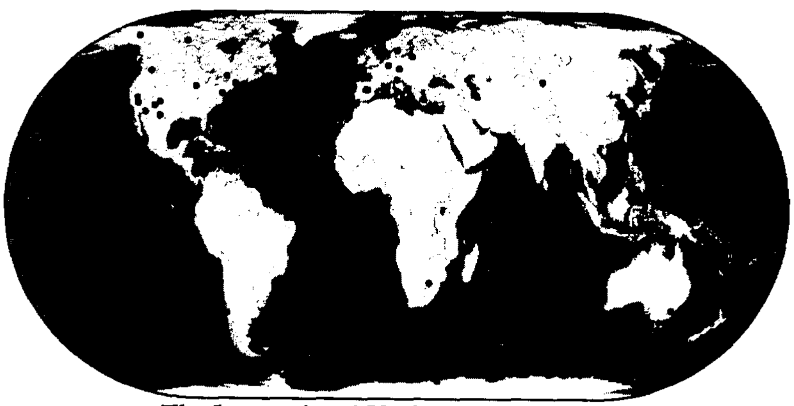
What does this imply for the individual space geodetic services? The continued vitality of the international services is critical to NGO and IGGOS success. The vast infrastructures and complex needs of the geodetic networks, shown in Fig. 2, require the expertise and dedicated attention provided by the individual services. As stressed in the IGGOS endorsement letter to the NGO proposal, this project will "fully take into account the IAG services." Indeed, it will bring them into closer harmony, in part to better serve their communities, and (not unrelated) in part to ensure their own long-term vitality. The individual techniques will continue their diverse activities, many of which lie outside the direct interests of NGO and IGGOS. But as the integration moves forward, some of those activities will be tailored to better serve the common interest.



The International GPS Service network



The International Laser Ranging Service network



The International VLBI Service network

Fig. 2. Geodetic Service Network Maps

Geodetic Performance Objectives

A central goal in unifying space geodesy, in addition to improving efficiency, is to reach new levels of performance through fusion of the different measurement types. Given the current high levels of performance achieved by all techniques it is fair to ask what potential science requirements might drive us to seek more. What specific measurement improvements may be needed to "keep ahead of societal requirements?"[19] While this topic will be explored in great depth during the early phases of NGO, we can hazard some tentative assessments.

Table 1. Approximate Space Geodetic Performance and Requirements

Product	VLBI	SLR	GPS	Science Req
TRF Global Components	*current*	*current*	*current*	*current - future*
Origin, 3D, Long-Term (mm)	n/a	1.0	tbd	1.0 - 0.3
Origin Rate, 3D, (mm/yr)	n/a	0.3	tbd	0.3 - 0.1
Geocenter, Monthly (x,y,z, mm)	n/a	3,3,10	3,3,10	n/a - 1,1,1
Scale, Long-Term (ppb)	0.2	0.3	1.0	0.2 - 0.1
Scale Rate (ppb/yr)	0.02	0.05	0.1	0.03 - 0.01
CRF				
Right ascension, declination (mas)	0.2	n/a	n/a	0.25, more sources
Station Location Components				
Coords, Long-Term (N,E,U, mm)	2, 2, 5	3, 3, 3	2, 2, 5	2, 2, 5 - 1, 1, 1
Linear Velocities (N,E,U, mm/yr)	1, 1, 2	2, 2, 2	1, 1, 3	1, 1, 3 - 1, 1, 1
Short-Term Motion (N,E,U, mm)	3,3,10, weekly	5,5,5, monthly	3,3,6, weekly	n/a - 1,1,3, daily
Earth Orientation Parameters				
Polar Motion (mas)	0.2, 3/wk	0.3, daily	0.1, daily	0.1 - 0.03, daily
Polar Motion Rate (mas/day)	0.4, 3/wk	0.6, daily	0.2, daily	0.2 - 0.03, daily
UT1 - UTC (μsec)	5, 3/wk	n/a	n/a	14 - 5, daily
Length of Day (μsec)	20, 3/wk	180, daily	20, daily	14 - 5, daily
Precession, Long-Term (mas/yr)	0.01	n/a	n/a	0.005
Nutation (mas)	0.2, 3/wk	n/a	n/a	0.05, daily
Satellite Parameters				
Satellite orbit ephemerides (cm)	n/a	2, varies	25, real time 5, 17 hours <5, 13 days	5, real-time 1, 13 days
Clocks (ns)	n/a	n/a	5, real time 0.2, 17 hours 0.1, 13 days	0.2-0.5, real-time 0.03, 13 days
Atmospheric Parameters				
Tropospheric Delays (mm)	5, hourly	n/a	6, 3 hours 4, weekly	tbd
Precipitable Water Vapor (mm)	0.7, hourly	n/a	0.6, hourly	0.5 - tbd, hourly

Table 1 summarizes the basic geodetic products delivered by the three services and gives their approximate current accuracy. The "requirements" are provisional at best; to help understand them, let's examine some of the science issues on which they rest, organized along two NASA solid earth research themes, "Geodynamics" and "Topography and Surface Change."

Geodynamics and Space Geodesy

The Geodynamics theme centers on observing and understanding the "motions of the earth and the earth's interior." We confine ourselves here to Earth rotational dynamics.

Earth rotation varies by up to 1 ms each day, and the earth wobbles and nutates as it rotates. Wobble and non-tidal rotation changes arise from angular momentum exchange between the solid Earth and its bounding fluids, and from internal deformations of the solid Earth. Precise rotation data can shed light on all of these processes.

Nutations. Earth's nutational response to gravitational forcing depends minutely on its interior structure. For example, nutation data have provided, a nonhydrostatic correction to the dynamical ellipticity of the core-mantle boundary, representing an increase of ~430 m in the difference of the equatorial and polar radii of the core-mantle boundary[20].

Tidal LOD changes. Earth's rotational response to the tidal forcing is likewise sensitive to its inner structure. Moreover, the lag of this response depends on dissipation processes within the Earth; with improved models of atmospheric and oceanic effects, this lag can shed light on mantle anelasticity[21].

Decadal LOD changes. Slow LOD variations over decades are thought to arise largely from core processes. Over the past century good agreement is found between decadal LOD data and the axial angular momentum of the core inferred from magnetics. This has led to new interpretations of core flow in terms of torsional oscillations[22].

Pole wander. Earth's rotation pole moves over the crust at ~10 cm/yr. This is thought to be largely due to postglacial rebound, although mantle convection and other effects may play a role. The postglacial rebound component depends directly on the viscosity of the mantle. The observed drift is routinely used to constrain postglacial rebound models[23].

Wobble resonances. The period of Earth wobble depends on internal structure, while the decay time can reveal internal dissipation processes[24]. Structural boundaries within the Earth produce related effects: The liquid core gives rise to a free core nutation; the solid inner core to an inner core wobble and nutation. Their periods and decay times can expose deep structure and dissipation processes.

With today's observing and modeling techniques, many subtle signals are as yet either undetectable or of uncertain import. Better measurements and models are needed before this discipline can begin to fulfill its promise.

Topography and Surface Change

The Topography theme centers on observing, understanding, and predicting the some-times violent processes of surface change. This simple theme masks an almost endless regress of subsidiary questions, among them:

- *What are the forces that drive plate boundary deformation?*
- *What determines the spatial distribution of plate boundary deformation?*
- *How has plate boundary deformation evolved?*
- *What controls the space-time pattern of seismicity?*
- *How do earthquakes nucleate?*
- *What are the dynamics of magma rise, intrusion, and eruption?*

- *How do the space-time scales of surface deformation vary with eruptive style and magma composition?*
- *Can we characterize surface change leading to eruptions and predict them reliably?*

To address these and similar questions we require knowledge of deformation and strain transients over time scales from seconds to decades and it is generally believed that we will ultimately need to reach sub-millimeter global accuracies.

The Global Reference Frame

Inseparable from the two research themes are the creation and maintenance of an absolute terrestrial reference frame (TRF) and its tie to inertial space, the celestial reference frame (CRF). The TRF/CRF provides the universal standard against which Earth is measured; it is the foundation on which solid Earth science rests. Deficiencies in the accuracy or continuity of the TRF/CRF system limit the quality of science it can support. Observable variations in the TRF/CRF – geocenter motion and rotation irregularities – are themselves primary signals in the science of Earth change. In other contexts, including the study of sea level change, land subsidence, crustal deformation, volcanic inflation, and ice sheet dynamics, reference frame control may be a primary limiting factor.

Each space geodetic technique makes a unique and critical contribution to the TRF/CRF. Other techniques are developing rapidly. How these evolving tools can best play together in coming decades is an open question that stands as a key challenge to our community.

Thumbnail Requirements Assessment

The signatures of interest in both Earth rotation and surface change can be surpassingly subtle. For that reason alone we see no immediate limit to the measurement quality that could *in principle* be of scientific value, if the measurements truly reflect the desired quantities. We do see a practical limit below which observed variations become irremediably confounded by extraneous effects – e.g., monument drift, atmospheric effects, hydrological processes – or obscured by geophysical modeling limitations. Such limits, however, will tend to recede as we better monitor, measure, and understand the myriad signals and processes embodied in the data. An ultimate limit is still far away.

At present we judge the practical useful limit to be very roughly a factor of 5 to 15 below today's measurement accuracies. If global geodesy is now accurate to roughly 1 cm (or 3-15 mm for different quantities), we see near-term utility in global measurements with accuracies between 0.1 and 1 mm. That sketchy analysis demands the community-wide scrutiny it will receive within the NGO and IGGOS projects.

Redundancy and Complementarity in Space Geodesy

To prepare the discussion of integration we first consider the space geodetic techniques in light of both their redundancy and their complementarity. As we see in Table 1, the three techniques measure many of the same quantities, often with comparable accuracy. This suggests a path to lower costs: trim duplication. While that, to be sure, will receive scrutiny, in the end it may offer less than one might suppose, for several reasons.

Redundant Rewards

Space geodesy has long pushed the frontiers of global measurement accuracy. One technique by itself, far in the advance guard, has difficulty assessing with any assurance its own performance. Comparisons with lesser techniques may avail little, except to cast unwarranted doubt on the pioneer. Or, equally vexing, an innovation in principle may in practice suffer from poorly understood systematic errors, early execution flaws, teething pains. Disparities with standard techniques may be wrongly ascribed to the latter. There are sufficient examples in our past of both varieties of confusion. For these reasons it is a boon to have several advanced techniques for mutual calibration and cross-validation. Indeed, it is the practice within the IAG and IERS to employ, where possible, at least two techniques for official products. Moreover, as we have seen repeatedly in space geodesy, a degree of healthy competition can be a spur to innovation and improved efficiency.

More fundamentally, the techniques of space geodesy, without exception, have irreplaceable uses outside of solid earth science: VLBI for astronomy, astrometry, and deep space navigation; SLR for studies in long term orbital dynamics, failsafe POD and validation, and space surveillance; GPS for navigation, surveying, time transfer, and meteorology – to name a few examples. They are vital tools for a growing worldwide community. For that reason, the best prospects for reduced cost to current sponsors lie less in trimming services than in improving their efficiency and attracting new sponsors from the growing hitchhiker class who have come to depend upon them.

Complementary Strengths

Of more immediate interest than redundancy is uniqueness: the complementary strengths of the three techniques and how they can be harnessed to improve performance.

Putting aside their separate uses outside solid earth science, each technique makes central geodetic contributions that are either unique or primary. VLBI alone delivers the CRF, along with precession and nutation, by observing stable sources at the edge of the visible universe, and provides the precise TRF scale. SLR, through use of dense, high-orbiting reflectors, enables unique studies of long-term orbital dynamics, provides the best tie to the earth center of mass, is the only failsafe means of precise orbit determination, and provides a definitive validation for other POD techniques. GPS enables low-cost global densification of surface change data, real-time operation, model-insensitive POD at low altitudes, and, at present, the only time-continuous geodetic observations.

If we then consider the extraordinary range of extended uses – astronomy, gravity recovery, meteorology, climatology, sun-earth connections, space weather, physical oceanography, and so on – the irreducible value of each technique is beyond question.

Paths to Improved Performance

In seeking improved accuracy we may consider two paths: enhancing the techniques individually to bring them closer to their practical limits; and integrating them tightly to tap their complementary strengths. These in no way conflict and, indeed, both must be followed if space geodesy is to reach its full potential. Refinement of the individual techniques will continue under separate initiatives. Deep integration, the central objective of NGO, may offer more immediate promise and remains largely untilled ground.

The IERS now combines final products from the individual services, but they do not as yet attempt combination at the data level. Full integration must be pursued on multiple levels, including planning, system analysis and design, network deployment, standards and models, operations, data combination, product generation, and quality control. NGO will explore the issues of combining raw observables at the earliest stage to create more accurate and robust synthetic products.

We see this as a pre-eminent challenge for space geodesy. After roughly a decade of basic development (~the 1980s) and another of refinement and global dissemination, the frontier is now integration and synthesis, with such derivative challenges as automated interpretation and understanding. Space geodetic products are becoming commodities, like computer chips, awaiting assembly into grander knowledge generation systems. NGO intends to help spearhead that advance within solid Earth science.

Towards Unification

The political challenges in uniting these independent, self-focused, and historically rival space geodetic techniques for a common purpose should not be minimized. As much care must be given to the process as to the research. The NGO campaign will encourage analysis centers to begin immediately acquiring skills in combining and analyzing all major data types to generate geodetic products. After decades of development, today's technique-specific analysis systems are highly refined and precise. Though compatibility and consistency issues will arise, cooperation among the techniques should quickly yield solutions. Key goals in the initial months will be to develop measurement requirements; review standards for data exchange; fashion an approach to federated governance; establish cross-technique committees (e.g., governance, requirements, products and services); specify a long-term agenda; create joint teams for integrated data analysis; and maintain an ongoing dialogue to facilitate unification.

As times and paradigms change, a realignment in space geodesy is becoming inevitable. But goodwill alone will not suffice to make this happen smoothly. Any perceived threat to one technique growing out of this campaign can nullify the best intentions. That is why diversifying the business base to assure stability and continuity to all, even as their roles within space geodesy evolve, is vital to success. A concerted initiative to broaden sponsorship is therefore essential. In that effort, the collective authority of a united space geodetic federation will far exceed what any technique alone can muster.

NGO comprises two central components corresponding to two overarching goals: (1) *Planning* to coordinate the campaign and shepherd the creation of a unified service, and (2) *Research* that will ultimately deliver a new generation of integrated geodetic products. In the next sections we enumerate some specific tasks within each class.

Research Tasks

Many technical questions must be resolved as we learn to integrate different data types into global geodetic products. These include:

- How do we establish science objectives and derived measurement requirements?
- How should we combine the data, given the divergent strategies that have evolved for SLR, VLBI, and GPS individually?
- What complications are introduced by the current mutually inconsistent models and methods of constraint used by different analysis centers?
- How can we move towards unconstrained solutions in an integrated service?
- How can our strategies be tailored to optimize for different products?
- How can we improve the short-term stability of the terrestrial reference frame?
- What quantities, relative and total, of each data type are needed?
- How can we optimally deploy observing stations?
- What will be the major error sources?
- What performance improvements can we expect to see over the next 5 years?
- What are the ultimate achievable and practical limits of performance?
- How can emerging space geodetic techniques improve things further?
- How do we maintain seamless continuity as we introduce new methods?

Some of these can be further parsed into more focused questions to be addressed one by one: e.g., distinguishing secular loading from tectonics, land subsidence from sea level change, thermal effects from mass change, mass and motion in Earth rotation; resolving subtle components of sub-daily polar motion; even agreeing on basic definitions for such things as geocenter motion, deformation, and surface motion. These issues become tightly coupled in geophysical studies. For example, we now have two distinct methods to detect geocenter motion (translation from conservation of momentum, and degree-one surface deformation). The translation rate of the origin affects angular velocities of plates. Separating secular loading from tectonics is essential. We require an appropriate "vertical datum" for global sea level studies and glacial rebound. IGGOS/NGO will offer a forum for addressing such issues.

Combining Data

A central question concerns how best to combine observations from different techniques to form precise, self-consistent geodetic products. There are two basic approaches: (1) combining at the "estimate" or "product" level, *after* each technique has processed its raw data into geodetic products; and (2) combining at the "data" or "normal equation" level to produce one set of integrated products from a mixture of raw observables. Each of these has its advantages, both practical and technical. Estimate level integration is more mature, though by no means perfected, and is used by the IERS, IGS, and other services to yield combined products. Data level integration represents the frontier and presents formidable practical challenges, but may be needed to enforce the consistency of models and assumptions believed critical to achieving the highest accuracies. There is a general belief that data level integration holds greater promise – if the practical problems can be overcome – but this is by no means a settled question.

A recurring issue in either approach is whether or how to apply constraints in the estimation process. The effects of constraints can be subtle. For example, constraining radiation parameters on the GPS satellites in various ways (a common practice) can alter the geocenter solution significantly. Analysis centers may be inclined to "optimize" their products by constraining those quantities they "know." Given the unfathomed observing strength of the combined techniques, such practices should be resisted until proven necessary. In general, constraints should be avoided.

The technical questions can be tackled by a variety of techniques: purely analytical; computer simulations and covariance analysis; and field experiments with real data. All of these will play a role in the course of this campaign. In the end, however, aggressive experimentation with mixed data and rigorous cross-comparisons among independent groups will be needed to identify the most effective strategies.

Technical Analysis

To address the technical issues of integration, NGO and IGGOS will jointly formulate a program of technical studies to be carried out by a set of cross-technique analysis groups. These groups will bring together the needed mix of skills and help forge the bonds across techniques required for campaign success.

The technical studies will be carried out under the direction of an overall IGGOS/NGO Research Coordinator. The consensus choice for that role is Dr. Markus Rothacher of the Technical University of Munich. As Analysis Coordinator for the International Earth Rotation Service (IERS), Dr. Rothacher has been immersed in the questions of technique integration, has begun to organize similar studies within the IERS, and has a similar role in IGGOS.

To begin, we have identified five core analysis groups, summarized briefly below.

Group 1: *System Review and Architecture* – This will carry out a review of the current techniques, their performance, costs, limiting errors, system requirements, and the like; define critical system performance and trade studies to be performed; define the different levels of integration needed; establish system functional and performance requirements; and shape the architecture for the integrated system.

Group 2. *Surface Change and the TRF* – This will focus on integration issues specific to topography and the TRF; carry out specific system performance studies; evaluate the effects of overt and subtle constraints in current solution strategies; refine "estimate-level" integration methods for the TRF; seek to improve short term (seasonal) stability; identify prospective technology enhancements; set milestones and performance goals.

Group 3. *Geodynamics and Earth Rotation* – This will be a counterpart to Group 2 for the Geodynamics research theme, conducting needed performance studies and addressing similar questions of limits, goals, constraints, solution strategies, estimate-level integration, etc, relating to observation and interpretation of Earth rotation parameters.

Group 4. *Data-Level Integration* – This will focus on the technical and practical problems of data-level integration, augmenting Groups 2 and 3. It will seek to identify and correct biases and inconsistencies between current analysis strategies, set standards, and find robust methods for data level intgegration.

Group 5: *Special Topics* – This will explore other subjects of interest to NGO, including real time products and operation, time transfer, atmospheric and ionospheric products, integration of LEO data into operations, enhanced data access, additional space geodetic techniques, and non-traditional applications.

The group titles and functions are at this point tentative. Over time their objectives will be tuned to maintain the focus on achieving an effective integration of techniques.

Relationship of NGO to IGGOS

To cement the international partnership NGO will include non-US co-investigators in all Analysis Groups. As IGGOS develops we expect these groups to expand and take on a stronger international flavor. From the standpoint of technical research, NGO and IGGOS activities should become essentially one large collaboration. However, NGO will retain its identity as a US umbrella organization to coordinate and unify the planning and practice of US space geodesy: to shape a common US system architecture and develop joint proposals to NASA and other US sponsors for the future development of SLR, VLBI, and GPS; to eliminate the fierce competition for resources through coordinated advance planning. NGO would continue its work, both in research and planning, even if IGGOS were to disappear.

INDIGO – The first NGO Implementation

The deep integration of space geodesy will unfold over years and will involve a good deal of research and experiment. An important unifying step we can undertake relatively quickly is to coordinate the disparate data systems maintained by the three services – the IGS, IVS, and ILRS. That is the goal of INDIGO, proposed under NASA's REASoN (Research, Education, Applications Solutions Networks) program as the first NGO implementation activity and selected in the summer of 2003. INDIGO seeks to improve performance and efficiency in the support of international Earth science research by providing ready, uniform access to heterogeneous and broadly distributed space geodetic data. INDIGO will build upon the services' existing data and information systems that have served users over the last decade. User interfaces will be integrated and streamlined, while access will be enhanced with advanced web-based services.

The INDIGO team will work with its user community to develop uniform standards and formats for all levels of data and metadata. Specifications will be developed through cooperation with the IERS, IGS, IVS, ILRS, IAG, IGGOS, and NGO. The GPS Seamless Archive (GSAC) philosophy[25], in which data at various locations are identified and served to users transparently, will be extended to all data types. To ensure that INDIGO is attuned to evolving science user requirements, a science advisory team (SAT), drawing on the NGO/IGGOS teams, will be established to provide direction and advice. This will be augmented by an international Inter-Service Working Group to ensure that INDIGO remains aligned with the services' policies and processes.

Table 2. INDIGO Goals and Objectives

Service System Unification and Integration
Develop a common catalog of existing services and products
Analyze interdependencies and identify synergies between current services
Develop and implement the structure to unify the services' data information systems via website INDIGO
Re-architect the independent services' data information systems
Develop and implement common interfaces for user access at each service where synergistic
Foster an international working group for the development and promotion of data and metadata standards
Present similar products side-by-side and uniformly formatted
Explore and implement 're-use' of GPS Seamless Archive philosophies/tools, extend to all techniques creating a Global Seamless Archive Center
Support and implement data processes for 'deep' inter-technique data integration
Enable combination of products in response to NGO/IGGOS
Provide reference frame data and products in support of IERS
Allow for data system inclusion of emerging technologies: altimetry, InSAR, space gravity, and magnetometry.
Conduct studies and experiments to address questions of proper data mix and locations of observing sites

Support to the Earth Science User Community
Provide precise geospatial/temporal data search as well as word search of information
Implement a station coordinate/velocity plots for all sites in cooperation with the IERS
Create a inter-technique Site Ties catalog designed to incorporate other techniques in the future
Prepare and publish the INDIGO Catalog of Observing Instruments and Stations (including GNSS constellation info)
Implement an auto-positioning service for investigators to submit/select data sets and return positions and information based on official inter-service products and IERS standards and conventions.
Investigate system and data integrity, with a forward-minded approach to GNSS (Galileo[27], GPS Modernization, GPS III) and Constellation civil integrity monitoring.
Develop INDIGO outreach and education activity to support users: displays, handout material attracting new users, on-line tutorials and material for user education and appropriate use of data & products
Combine and upgrade the web based directory of colleagues for the few thousand current users, enable expansion for many new users

Responsiveness to Science Drivers
Establish a Science Advisory Team for direction on developments closely associated with developing scientific requirements of IGGOS/NGO; INDIGO directly supports these activities (of expert users) while continuing to serve broad Earth science users

At present, as we have noted, the central offices of the IGS, IVS and ILRS develop and maintain independent data systems. In addition, the data system established by the Crustal Dynamics Project (CDP), the Crustal Dynamics Data Information System (CDDIS)[26] serves as a repository for all space geodetic data types collected by NASA and its partners and will provide the core and starting point for INDIGO. In short, INDIGO seeks to build upon the successes of each service and the CDP to provide an ensemble information service whose utility to geodetic science exceeds the sum of its parts. Table 2 summarizes the key goals and objectives for INDIGO.

The unified face of INDIGO, accessible on the world wide web, will allow a single point of entry to the combined IGS, ILRS, and IVS data products, as well as a route to the technique-specific information services. Each geodetic service will continue to maintain cognizance of its own information systems. Areas common across the services will be re-engineered to meet agreed-upon characteristics, including uniformity of presentation.

NASA's Geodetic Data System and Archive: CDDIS

The CDDIS, which will provide the foundation for INDIGO, is a dedicated data center supporting the international scientific community as NASA's space geodesy data archive since 1982. The CDDIS currently serves as one of several global data centers for each of the IGS, ILRS, IVS, and the future International DORIS Service (IDS).[28] The CDDIS provides ready access to a variety of data products, and related information. Most data are accessible to scientists through both ftp and the web, while general information about the data set is accessible via the web. The CDDIS website allows users to generate limited special and temporal queries to determine and access the on-line archive. The CDDIS staff and computer facility are located at NASA GSFC in Greenbelt, MD.

Approach to Data Distribution and User Support

INDIGO will offer a unified web presence that automatically draws from the technique-specific information systems. Data distribution will be augmented by geospatial search tools and GSAC capabilities which present data form the distributed sources as if from a single archive. User support will be strengthened with search capabilities, uniformity of presentation, and tutorial materials. Cost benefits are found in leveraging existing service structures and expertise, as well as by leveraging in-kind support from existing projects within the services. The GSAC effort has developed viable architectures and tools for GPS data, enabling cost-beneficial reuse in extending the concept to other data types.

Those who perhaps stand to benefit the most from INDIGO are new or infrequent users. The burden of learning the inner workings of archives and stations would be lessened by the adoption of common metadata practices and a single instruction on data searching with a GSAC client.

INDIGO will automatically integrate information from the technique-specific systems. For example, the INDIGO publications area will consist of a presentation "shell" in which the listed publications are dynamically updated from the lists on each service's system. Participating services are in this way freed from making duplicate updates, and the currency of information provided by INDIGO is ensured. The features of each service's common web areas will be revised for easy machine readability to enable this.

Distribution of End Products

INDIGO is intended to be a long-term archive, as required by the nature and uses of geodetic data sets and products. INDIGO will provide for the distribution of all end-products of space geodetic research, including complete documentation, metadata, publications, ancillary information, peer-reviewed publications and a wealth of links. In addition, all relevant email traffic is archived to trace the development of issues and solutions among user community.

NGO Planning Activities

Effective planning is critical to the success of IGGOS and NGO. Some of the key issues facing us, and our thoughts for addressing them, are summarized below.

Extended Participation – As we prepare for formal launch, NGO and IGGOS will jointly release an open call for voluntary participation. All respondents with an active interest in the integration of space geodesy who are willing to contribute their time and energy will be welcome to take part.

Governance Structure – A formal governance structure will be created, drawing upon experience with such bodies as the IERS, ESIP Federation, SCIGN, and IAG services, to take effect within two or three years. An interim structure is given in the proposal.

Legal Status – The legal configuration of NGO will be decided by the membership. There are recent examples – UNAVCO[29], the ESIP Federation[30] – of groups constituting themselves as independent "legal entities" or corporations. We envisage something along those lines, perhaps modeled on the ESIP Federation's dual incarnation as a not-for-profit corporation (which includes many commercial, for-profit partners) and an associated Foundation for developing new business and receiving funds.

Broader Sponsorship – As the use of space geodetic products spreads, new funding opportunities grow in step. Within NASA, space geodesy has been nurtured almost entirely within the relatively modest solid earth research program. Yet it now plays vital roles not only throughout Earth science, but in space science, human flight, mission operations, national defense, and civil navigation. Those programs have greater resources than SENH and enjoy benefits from the geodetic services of comparable value, and yet contribute little or nothing to their development and upkeep.

Spacecraft navigation is a telling example. Traditionally, NASA has maintained stable, well funded, mission-independent programs to provide for the tracking needs of its flight missions, complete with advanced technology and operations budgets: e.g., the Spaceflight Tracking and Data Network (STDN), the NASA Polar Network (NPN), TDRSS, the Deep Space Network (DSN). Their annual budgets dwarf the SENH research funds that sustain SLR, VLBI, and GPS. Yet flight projects are coming to depend more and more on the geodetic systems for their operational needs. Here are a few examples:

VLBI provides Earth rotation and timing data essential to the estimable feats of interplanetary sharpshooting now taken for granted. More recently, direct VLBI spacecraft navigation ("ΔDOR") was used for the celebrated Mars Odyssey orbit insertion and aerobraking; it is now mandated for navigation of all future deep space missions. The exhaustive astrometric source catalog development and maintenance needed for ΔDOR is little distinguishable from the regular VLBI observations conducted for geodesy. Surely the latter can benefit from NASA's renewed support for VLBI navigation.

SLR is an indispensable and virtually failsafe method for precise LEO orbit determination, now a mainstay of NASA and international science missions: Topex/Poseidon, CHAMP, Jason-1, GRACE, ICESat, VCL, ERS-1 and -2, Envisat. Moreover, with is peerless sub-centimeter ranging accuracy, SLR provides the only "absolute" validation for other precise LEO tracking systems. These missions are typically in the $200M-$500M class, yet the cost for this mission-critical tracking function is borne almost entirely by the comparatively paltry SENH research budget.

GPS has emerged as a workhorse of LEO orbit determination, both precise and routine, and is carried by nearly every new mission that flies. GPS is attractive because it is both highly accurate and operationally cheap – in some cases virtually autonomous – and in fact can provide substantial autonomy and related economies across the mission. POD with GPS is cheap because of, and only because of, the seminal support by SENH and other geodetic sponsors in deploying and maintaining the extensive global ground network; retrieving, archiving, and analyzing the data; generating the full suite of geodetic and GPS orbit products; and delivering them instantly at no charge.

Until recently, precise orbit determination (POD) was considered experimental, needed only for esoteric science, and thus was required by NASA to be provided with research funds. Because geodesy had laid the foundations – ground systems, product generation – even today's flight science projects have been able to ride along relatively freely. While that may have made some sense in the exploratory era, the ground has now shifted. Today, POD is integral and indispensable to a new generation of operational flight projects. It is neither reasonable nor prudent that mission success should rest upon uncertain and declining research funds. It is time for the multi-mission support model to be applied, or for the missions themselves to underwrite the services they demand.

Space doesn't permit a full airing of the cost sharing possibilities. Other prospects within NASA, apart from spacecraft navigation, are cited above. And NASA is not the only, or even the largest, US space agency. Spacecraft requiring POD are lofted by the DoD, NOAA, IPO, intelligence services, and commercial interests, not to mention numerous international powers. Moreover, navigation and POD are but one sector of the space geodesy customer base. Others include the national geodetic reference frame, surveying, GIS applications, atmospheric and ionospheric research, meteorology, aviation, and other real time positioning users. The roster grows each year.

To tap these expanding user groups we propose to hold a conclave of US agencies that benefit from space geodesy and the global reference frame. These would include various NASA groups, NOAA (NGS, Office of Coast Survey, National Ocean Service, Weather

Service), DOT (Coast Guard, FAA, NDGPS network), DOI (USGS), NSF, DoD (GPS Ops, JPO, NIMA, USNO), IGEB, Federal Geodetic Control Subcommittee (FGCS) and GIAC. The purpose is to expose the critical role of space geodesy to the many users who do not contribute to it, and to devise approaches for cost recovery. In parallel we will work with the IAG to initiate a similar dialogue with international user groups – ICAO, UNESCO, GNSS overlay services, and so on. The U.S. and international efforts will be coordinated to converge on a unified global approach.

Joint Proposals – The Strategic Plan will contain recommendations for joint action – new technology initiatives, special study groups, new roles or technical directions – endorsed by the membership. From those recommendations NGO will encourage cross-technique proposals to prospective sponsors. We can expect such proposals, carefully vetted and carrying the NGO imprimatur, to carry added weight and credibility.

Incorporating Other Techniques – NGO is conceived to embrace all of space geodesy, including such developing forces as DORIS, InSAR, altimetry, and space gravimetry. Because the challenges of federating the current services are formidable, we have chosen here not to include further expansion as a formal objective. However, full inclusion is integral to the NGO concept and we intend to reach out to those groups early on. The onus is on the founders to build a federation of such evident value and authority that others will want to become a part.

Final Comment

Anxieties over asymmetric budget cuts within a divided discipline have done more to harden those divisions than any other factor. We see that at work today within the NASA program. By forging a deep alliance we can help to ensure that the rewards from future successes are shared to some degree by all, and that participants begin to identify their interests more with the integrated observatory than with individual techniques. It has been observed that certain politically astute science communities – astronomy and to some extent physics – are consistently able to submerge their differences to rally behind targeted initiatives, vastly magnifying their influence and enjoying repeated successes in advancing their most cherished programs. This observation is at times made in pointed contrast to the sporadic factionalism within SES. We see the federation as a step towards reversing the decline of geodesy and solid Earth science within NASA by shifting our focus away from unconstructive rivalries and back to the fundamental science and the societal needs that first drew us to this vocation.

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